

NON-SWITCHING ADAPTABLE 4-WAY POWER SPLITTER/COMBINER

Field of the Invention.

[0001] The present invention relates to combining and splitting high power, high frequency RF signals and, more particularly, to a device that splits such signals to provide inputs for 1 to 4 amplifiers and then combines the output signals from the individual amplifiers to produce a single amplified output.

Background

[0002] Modern RF circuits often require amplified signals that are produced by splitting an input signal, providing it to a number of amplifier modules and then combining the output of the amplifier modules into a single amplified output signal. Often it would be beneficial to employ a circuit in which the number of amplifier modules can be increased or decreased as conditions demand. This allows initial construction of an operative amplifier circuit with a single amplifier module and subsequent addition of one to three amplifier modules to the circuit as technical needs require additional amplification or as financial constraints allow investment in additional amplifier modules.

[0003] Conventionally, power splitting and power combining in RF circuits is performed using Wilkinson type power divider/combiner systems, as generally described in "An N-Way Hybrid Power Divider" by E.J. Wilkinson, *IRE Transactions on Microwave Theory and Techniques*, Vol. MTT-8, No. 1, January 1960, at pp. 116-118. A deficiency of pure Wilkinson type systems is that they operate efficiently only when all of the branches of the divider/combiner include a properly operating amplifier module. If an amplifier module is missing or inoperative, the Wilkinson type divider or combiner loses efficiency because of the impedance mismatch presented by the inoperative/absent amplifier module.

[0004] As a result, there have been a variety of attempts to modify Wilkinson type divider combiners to overcome the difficulties presented by inoperative amplifiers. One such attempt is described in U.S. Patent No. 5,543,751 to Stedman. Through the use of phasing lines and matching lines, each having a specific length and impedance, the Stedman power combiner is capable of acceptable efficiency if one or more of the installed amplifiers should fail. That is, the power loss if 1, 2 or 3 of the installed amplifiers fails (in a four-amplifier system), does not exceed 11% of the input power. In addition, to operate properly the Stedman device requires that all amplifier positions be populated with an amplifier.

[0005] Another attempt to solve the difficulty of inoperative amplifiers is described in U.S. Patent No. 5,767,755 to Kim. Again, through the use of phasing lines and matching lines, each having a specific length and impedance, the Kim power combiner is capable of operating at acceptable efficiency levels even if one or more of its amplifiers fail. That is, the power loss if 1, 2 or 3 of the installed amplifiers fails, does not exceed 11% of the input power. To operate properly, the Kim device requires that all amplifier positions be populated with an amplifier.

[0006] A more complicated method of addressing the difficulty posed by inoperative amplifiers is described in U.S. Patent No. 4,315,222 to Saleh. The power combiner disclosed in Saleh requires switches and sensing means to maximize performance of the network in case one of the amplifiers fails. When a failed amplifier is sensed, the switches alter the presented impedance to maintain an acceptable level of efficiency. The switches and sensing means of that network increase its complexity and cost.

[0007] The power combiner/splitter networks disclosed in Stedman, Kim and Saleh are designed to operate with a specific number of amplifier modules, and further, to provide acceptable levels of signal loss in the case that one or more of the amplifier modules should fail. Furthermore, each is designed to operate properly only when all available amplifier

positions are populated with an amplifier. They are not designed to allow population of less than all amplifier positions or to permit subsequent addition of one or more amplifiers.

[0008] European Patent EP 0540286B1 to Japan Radio Co., Ltd. discloses a power divider combiner that will operate even when less than all of the amplifier positions is populated. The circuit disclosed in EP 0540286B1, however, must be designed to maximize performance when a selected number of amplifier modules is populated. When more or fewer amplifier positions are populated, performance of the circuit suffers. For example, if the circuit is designed as a four-way circuit that is maximized for performance when three amplifier positions are populated, the return loss when 1, 2 or 4 amplifier positions are populated will be higher than when 3 positions are populated.

[0009] What is needed is a four-way power splitter and combiner network that is capable of operating at acceptable efficiency when populated with one, two, three or four amplifier modules and that further provides acceptable signal attenuation and Voltage Standing Wave Ratio (“VSWR”) if the network is populated with less than four amplifier modules.

Summary

[0010] The present invention is suitable for splitting an input signal into one to four transmission paths, which are then amplified by one to four amplifier modules that are installed or removed in a particular order. After amplification, the present invention combines the signals into a single, in-phase amplified signal. For example, if the circuit is configured as a “back plane” with four amplifier ports and one of those ports is populated, then the populated port is port 1 or 2 and all unused ports are open-circuited at the unused amplifier ports. If the amplifier is installed in port 1, a second amplifier can be added by simply installing it in port 2. A third and fourth amplifier can be installed in ports 3 and 4. It

is not necessary to reconfigure the circuit to produce acceptable levels of return loss for each operating condition (i.e., 1, 2, 3 or 4 amplifier modules installed).

Brief Description of the Drawings

[0011] The present invention will be more fully understood and appreciated by reading the following Detailed Description in conjunction with the accompanying drawings, in which:

[0012] Fig. 1 is a schematic of an embodiment of the present invention.

[0013] Fig. 2 is a schematic of a portion of an embodiment of the present invention.

[0014] Fig. 3 is a schematic of another portion of an embodiment of the present invention.

[0015] Fig. 4 is a schematic of the preferred embodiment of the present invention.

[0016] Fig. 5 is a schematic of a portion of an alternate embodiment of the present invention.

Detailed Description

[0017] Referring now to Figure 1, there is seen a splitter/combiner 10 according to the present invention, comprising a splitter portion 100 and a combiner portion 120. The splitter portion 100 comprises an input port 101, two nodes 102, 103, a plurality of transmission lines 104, 105, 106, 107, 108, 109, and four amplifier inputs 110, 112, 114, 116. The combiner portion 120 comprises an output port 121, two nodes 122, 123, a plurality of transmission lines 124, 125, 126, 127, 128, 129, and four amplifier outputs 130, 132, 134, 136. The elements of the combiner portion 120 mirror corresponding elements of the splitter portion 100, except for the phase shift produced by the transmission lines 104 – 109, 124 - 129, as will be further described hereinbelow. More specifically, each amplifier input 110, 112, 114, 116 corresponds to an amplifier output 130, 132, 134, 136 and each pair of corresponding

amplifier inputs and outputs (e.g., amplifier input 110 and amplifier output 130) defines an amplifier port 140, 142, 144, 146. Each amplifier port 140, 142, 144, 146 can accept an amplifier module 150 (see fig. 4).

[0018] In operation, each amplifier port is either populated with an operating amplifier module or is left open. An open amplifier port can either be an amplifier port that is not populated with an amplifier module or one that is populated with an amplifier module that has been selectively switched to present an open circuit. As used herein, an inactive amplifier port means an amplifier port that presents an open circuit, either because it is not populated with an amplifier module or because it is populated with an amplifier module that has been selectively switched to present an open circuit. Because inactive amplifier ports present an open circuit, the length of each transmission line 104 – 109, 124 - 129 must be carefully selected to present the correct impedance in each operating condition (i.e., when 1, 2, 3 or 4 amplifier modules is installed) and also to properly shift the phase of the signal in each branch of the circuit such that the signal is in phase at the output port 121. Those skilled in the art will recognize that out-of-phase signals and incorrect impedances will reduce the efficiency of the splitter/combiner network.

[0019] Referring now to Figure 3, there is depicted the splitter portion 100 and amplifier ports 140, 142, 144, 146 according to a first embodiment of the invention. For simplicity of description, the combiner portion 120 is not depicted. Those skilled in the art will recognize that the principles disclosed herein with respect to splitter portion 100, however, are equally applicable to the combiner portion 120. As will be further described hereinafter, however, the electrical lengths of elements in the combiner portion 120 are not the same as the lengths of counterpart components in the splitter portion 100. The input port 101 functions as a two-way junction, as do each of the nodes 102 and 103.

[0020] All amplifier ports 140, 142, 144, 146 are assumed to be 50-ohms when populated with an amplifier module 150. Referring again to Figure 1, the length and impedance of each transmission line 104 – 109 and 124 - 129 is selected so that when only one branch of any of the junctions (i.e., input port 101, output port 121, nodes 102, 103, 122, 123) contains an active amplifier port, the energy from the active amplifier port(s) reflects off the open port(s) and is seen as an open circuit at the nearest junction, provided that the amplifier ports 140, 142, 144, 146 have been populated in sequence as disclosed herein.

[0021] According to the present invention, if the splitter/combiner 10 is populated with less than four amplifier modules 150, the amplifier ports 140, 142, 144, 146 are populated in a predetermined sequence. For example, if the splitter/combiner 10 is populated with only one amplifier module 150, that amplifier module 150 should populate first amplifier port 140 or second amplifier port 142. If the splitter/combiner 10 is populated with two amplifier modules, those amplifier modules 150 should populate first amplifier port 140 and second amplifier port 142. If the splitter/combiner 10 is populated with three amplifier modules 150, those amplifier modules 150 should populate first amplifier port 140, second amplifier port 142, and one of either third amplifier port 144 or fourth amplifier port 146.

[0022] Each possible path from the input port 101 through amplifier modules 150 and to output port 121 must have the same electrical length. That is, the phase change from the input port 101 to the output port 121 must be equal through each of the possible paths through which a signal can travel. The difference in electrical length from the input port 101 to first node 102 and from the input port 101 to second node 103 is 90 degrees. The difference in electrical length from the output port 121 to third node 122 and output port 121 to fourth node 123 is also 90 degrees. The signal produced at the output port 121 must be completely in phase. That is, if the input port 101 to first node 102 signal is +90 relative to the input port 101 to second node 103 signal, then the output port 121 to third node 122

signal must be -90 relative to the output port 121 to fourth node 123 signal. The relationship may also be reversed such that the input port 101 to first node 102 signal is -90 relative to the input port 101 to second node 103 signal and the output port 121 to third node 122 signal is +90 relative to the output port 121 to fourth node 123 signal.

[0023] Referring now to Figure 2, there is depicted a part of the splitter portion 100, comprising input port 101, transmission lines 104, 105, 106, first node 102, first amplifier input 110 and second amplifier input 112. In addition, first amplifier output 130 and second amplifier output 132 are depicted, which with first amplifier input 110 and second amplifier input 112, respectively, define first amplifier port 140 and second amplifier port 142. Those skilled in the art will recognize that the structure of the splitter portion 100 is mirrored by the structure of the combiner portion 120 (see Figs. 1, 4), except for the phase shift produced by the transmission lines 104 – 109, 124 - 129, as will be further described hereinbelow. As disclosed above, where only one amplifier port 140, 142, 144, 146 is populated it must be either first amplifier port 140 or second amplifier port 142. The other of these two amplifier ports 140, 142 will be inactive. For purposes of example only, Fig. 2 depicts an amplifier 150 populating first amplifier port 140. In this example, second amplifier port 142 is inactive. The length of transmission lines 105 and 107 must be selected such that the standing wave produced in transmission line 107 from first node 102 to the inactive amplifier port 142 must appear open circuited at first node 102. The impedance at the input port 101 will be 35.35 ohms, or some other reasonable impedance less than 50 ohms, transformed from 50 ohms at the active amplifier port (which in this example is first amplifier port 140).

[0024] In similar fashion, the length of transmission lines 108, 109 (see Fig. 3) must be selected such that when only one of amplifier ports 144 and 146 is populated, the standing wave produced in the transmission line between second node 103 and the inactive amplifier port appears open circuited at second node 103.

[0025] Referring now to Figure 3, there is depicted the splitter portion 100, comprising input port 101, transmission lines 104 – 109, first node 102, second node 103, first amplifier input 110, second amplifier input 112, third amplifier input 114 and fourth amplifier input 116. Also depicted are first amplifier output 130, second amplifier output 132, third amplifier output 134 and fourth amplifier output 136, which with first amplifier input 110, second amplifier input 112, third amplifier input 114 and fourth amplifier input 116, respectively define first amplifier port 140, second amplifier port 142, third amplifier port 144 and fourth amplifier port 146. As described above, where only three amplifier ports are active, the active amplifier ports must be first amplifier port 140, second amplifier port 142, and one of either third amplifier port 144 or fourth amplifier port 146. For example purposes, Fig. 3 further depicts amplifier modules 150 populated in first amplifier port 140, second amplifier port 142 and third amplifier port 144. The standing wave produced in the transmission line from second node 103 to the inactive port (which in this example is fourth amplifier port 146) must appear open circuited at second node 103. The impedance at the input port 101 is 47.2 ohms, or some other impedance such that amplitude balance and return loss are reasonable. The impedance at the input port 101 is the result of the parallel combination of the impedance looking back into the path from third amplifier port 144 and fourth amplifier port 146, and the impedance looking back into the path from first amplifier port 140 and second amplifier port 142.

[0026] Referring now to Figure 4, a splitter/combiner according to the preferred embodiment is depicted along with amplifier modules 150 populating the amplifier ports 140, 142, 144, 146. In the preferred embodiment the impedance transform from first amplifier port 140 to first node 102 comprises transmission line 105 and the impedance transform from second amplifier port 142 to first node 102 comprises transmission line 106, each of transmission lines 105, 106 comprising a segment having 50-ohms impedance and 270

degrees electrical length, and a segment having a 90-degree electrical length and an impedance of 59.46 ohms. The transmission lines 105, 106 must comprise one segment that is 90 degrees in length and a segment that is either 90 degrees in length or an odd multiple of 90 degrees. The impedance transform from first node 102 to the input port 101 comprises a transmission line 104 that is 90 degrees in length and has an impedance of 50 ohms.

[0027] The impedance transform through the segment of transmission lines 105 and 106 having impedance of 59.46-ohms is 50-ohms to 70.7-ohms seen at first node 102. The value of 70.7-ohms is selected because it is the geometric mean of the output impedances of a splitter/combiner 10 according to the present invention in which one amplifier port is active (50-ohms) and one in which two amplifier ports are active (100-ohms). The segment of transmission lines 105, 106 having impedance of 50-ohms must have a length selected so that the total electrical length from first amplifier port 140, through first node 102 to second amplifier port 142 is 360 degrees or a multiple of 360 degrees so that when one of amplifier ports 140, 142 is open the energy from the active amplifier port reflects off the open amplifier port and is seen as an open at first node 102. This open in parallel with the 70.7-ohm impedance at first node 102 will result in 70.7-ohm impedance. Therefore, in the case of one active amplifier port, the impedance at first node 102 is 70.7-ohms. The impedance is then transformed to 35.35-ohms through transmission line 104, which has an impedance of 50 ohms and an electrical length of 90 degrees, to the input port 101. VSWR is 1.42:1 or 15.22dB return loss, with loss due to mismatch equal to 0.13dB.

[0028] In both the splitter and combiner where only two amplifier ports are active, the impedance at the input port 101 will be 70.7 ohms, or some other reasonable impedance greater than 50 ohms, transformed from the lower impedance of the parallel combination at first node 102.

[0029] In the case of two active amplifier ports (first amplifier port 140 and second amplifier port 142), first node 102 results in the parallel combination of the two active amplifier ports which are 70.7-ohms each which equals 35.35-ohms. When transformed through transmission line 104, the result is 70.7-ohms at the input port 101. VSWR is 1.42:1 or 15.22dB return loss, with loss due to mismatch equal to 0.13dB.

[0030] The impedance transform from third amplifier port 144 to second node 103 comprises a transmission line 108 of 50 ohms impedance and the impedance transform from fourth amplifier port 146 to second node 103 comprises a transmission line 109 of 50 ohms impedance. Transmission line 108 and transmission line 109 each have a length of 180 degrees or any other even multiple of 90 degrees. From second node 103 to the input point 100 comprises a transmission line 107 having a segment with electrical length of 90 degrees and an impedance of 38 ohms and another segment having an electrical length of 90 degrees and an impedance of 64 ohms.

[0031] In both the splitter and combiner when all four amplifier ports are active, the impedance at the input port 101 or output port 121 will be 70.7 ohms, or some other impedance such that amplitude balance and return loss are reasonable. The impedance at the input port 101 or output port 121 is the result of the parallel combination of the impedance looking back into the path from third amplifier port 144 and fourth amplifier port 146, and the impedance looking back into the path from first amplifier port 140 and second amplifier port 142.

[0032] The impedance transform through transmission line 107 to the input port 101 is either 50-ohms to 142-ohms when one of amplifier ports 144 and 146 is active, or 25-ohms to 70.7-ohms when both amplifier ports 144 and 146 are active. The 50-ohm transmission line from third amplifier port 144 and fourth amplifier port 146 must be such that when one of these amplifier ports is open the energy from the active amplifier port reflects off the open

amplifier port and is seen as an open at second node 103. This open in parallel with the 50-ohm impedance at second node 103 will result in 50-ohm impedance. Therefore, in the case of one of amplifier ports 144 and 146 being active, the impedance at second node 103 is 50-ohms. The impedance is then transformed to 142-ohms through transmission line 107 to the input port 101.

[0033] In the case both third amplifier port 144 and fourth amplifier port 146 are active, the impedance at second node 103 is the parallel combination of the impedances of the two active amplifier ports 144 and 146 at 50-ohms each, which equals 25-ohms. When transformed through transmission line 107, the result is 70.7-ohms at the input port 101.

[0034] When both third amplifier port 144 and fourth amplifier port 146 are open circuited, the reflection from either of those ports at the input port 101 must also be an open circuit. As discussed before, second node 103 must appear as an open when one of either amplifier port 144 or amplifier port 146 are active. Therefore, the impedance transform from second node 103 to the input port 101 is a transmission line 107 having a two-segment (180-degree) transformer, which appears open at the input port 101 when both third amplifier port 144 and fourth amplifier port 146 are open.

[0035] When first amplifier port 140, second amplifier port 142, and one of third amplifier port 142 or fourth amplifier port 146 are active, the input port 101 impedance is equal to the parallel combination of 70.7-ohms from first amplifier port 140 and second amplifier port 142, and 142-ohms from the active amplifier port of third amplifier port 144 or fourth amplifier port 146. The result is 47.2-ohms. VSWR is 1.062:1 or 30.39dB return loss.

[0036] When all four amplifier ports are active, the impedance at the input port 101 is equal to the parallel combination of 70.7-ohms and 70.7-ohms. The result is 35.35-ohms. VSWR is 1.42:1 or 15.22dB return loss, with loss due to mismatch equal to 0.13dB. Table 1

shows a summary of the input port impedance, VSWR and return loss, with loss due to mismatch equal to 0.13 dB.

[0037] The purpose of the impedance transformation in transmission lines 104 – 109, 125 – 129 is to transform the impedance of amplifier modules 150, which is assumed to be $50\ \Omega$, to an acceptable impedance at input port 101 and output port 121. Generally, an acceptable impedance at input port 101 and output port 121 will be between approximately $35.35\ \Omega$ and $70.7\ \Omega$. Those skilled in the art will recognize that the principles disclosed herein with respect to impedance selection for transmission lines 104 – 109 in the splitter portion 100 apply equally with respect to transmission lines 125 – 129 in the combiner portion 120. Moreover, those skilled in the art will recognize that impedance transformation equivalent to that produced by can be accomplished by transmission lines that have more segments than depicted in Fig. 4, provided that 1) the electrical length of each path through transmission lines 104 – 109, 125 – 129 satisfies the equations set forth below, and 2) the impedance of each segment is selected to produce impedance transformation for each of transmission lines 104 – 109, 125 – 129 that is generally equivalent to that depicted in Fig. 4.

[0038] Referring now to Figure 5, there is depicted an alternate embodiment, in which the splitter portion 500 has an input port 501 which functions as a three-way junction and one node 502, which functions as a two-way junction. The transmission lines from third amplifier port 544 and fourth amplifier port 546 can be joined directly to the input port 501. If the two transmission lines are routed directly to the input port 501, they must appear open to the input port 501 when they are not active. In this embodiment, when all four amplifier ports 540, 542, 544, 546 are active, the impedance transform will result in $35.35\ \Omega$ at the input port 501, or some other impedance such that amplitude balance and return loss are reasonable. As described below, the structure of the combiner portion 520 (not shown) according to this embodiment will mirror that of the splitter portion 500.

[0039] Table 1 shows a summary of the impedance (as viewed from input port 101 or output port 121, VSWR and return loss under the various conditions using the circuit depicted in Figure 4 as an example.

Table 1

Condition	Impedance	VSWR	Return Loss	Loss (%)
1-Way	35.35-ohms	1.42:1	15.2 dB	3
2-Way	70.7-ohms	1.42:1	15.2 dB	3
3-Way	47.2-ohms	1.06:1	30.4 dB	0
4-Way	70.7-ohms	1.42:1	15.2 dB	3

[0040] As described herein, the splitter portion 100 generally mirrors the combiner portion 120. That is, each component of the splitter portion 100 is mirrored by a corresponding component in the combiner portion. For example, the input port 101 corresponds to the output port 121 and transmission line 109 corresponds to transmission line 129. In general, corresponding components have the same electrical characteristics. For example, in the preferred embodiment depicted at Figure 4, transmission line 109 and transmission line 129 both have an impedance of 50 ohms and an electrical length of 180 degrees. This correspondence relationship does not hold true for the electrical length of transmission lines 105, 106, 125 and 126.

[0041] Figure 4 shows the phase relationship between all the ports on both the splitter and combiner in the preferred embodiment. The impedances of transmission lines 105 and 106 are the same as the corresponding transmission lines 125 and 126. The electrical lengths of transmission lines 105 and 106, however, differ by 180 degrees from the electrical lengths of transmission lines 125 and 126. This is done so that all four paths from the input port 101 to the output port 121 have the same electrical length necessary for properly combining coherent signals. Neither the splitter portion 100 nor the combiner portion 120 are stand-

alone circuits due to the phase relationships between the input port 101 and output port 121. The splitter portion 100 and the combiner portion 120 are designed to work together, as it is necessary to realign the phases after amplification.

[0042] According to the present invention, the relationship of the electrical lengths through each possible path of the splitter/combiner must satisfy the following equations, where Φ is the electrical length of a transmission line segment:

$$\Phi_{(\text{transmission line 104})} + \Phi_{(\text{transmission line 105})} = \Phi_{(\text{transmission line 104})} + \Phi_{(\text{transmission line 106})} = X$$

$$\Phi_{(\text{transmission line 107})} + \Phi_{(\text{transmission line 108})} = \Phi_{(\text{transmission line 107})} + \Phi_{(\text{transmission line 109})} = Y$$

$$\Phi_{(\text{transmission line 124})} + \Phi_{(\text{transmission line 125})} = \Phi_{(\text{transmission line 124})} + \Phi_{(\text{transmission line 126})} = X'$$

$$\Phi_{(\text{transmission line 127})} + \Phi_{(\text{transmission line 128})} = \Phi_{(\text{transmission line 127})} + \Phi_{(\text{transmission line 129})} = Y'$$

[0043] According to the present invention, the electrical length of the path from input port 101 through first node 102 to amplifier inputs 110, 112 differs from the electrical length of the path from input port 101 through second node 103 to amplifier inputs 114, 116. In addition, the electrical length of the path from output port 121 through third node 122 to amplifier outputs 130, 132 differs from the electrical length of the path from output port 121 through fourth node 123 to amplifier outputs 134, 136. The difference in each case is 90 degrees, or described using terms of the above equations, $|X - Y| = 90$ and $|X' - Y'| = 90$. Furthermore, the difference in the electrical length between the path through first node 102 and second node 103 is the opposite of the difference in electrical length between the path through third node 122 and fourth node 123. That is, $(X - Y) = (Y' - X')$.

[0044] While there has been illustrated and described what is at present considered to be the preferred and other embodiments of the invention, it should be appreciated that changes and modifications are likely to occur to those skilled in the art. It is intended in the appended claims to cover all those changes and modifications that fall within the spirit and scope of the present invention.